Measuring Cloud Properties from Space: A Review

WILLIAM B. ROSSOW

NASA Goddard Space Flight Center, Institute for Space Studies, New York, N.Y.

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ABSTRACT

A brief review of observations of clouds using satellites highlights open issues and directions for future studies. The key one is improved treatment of the effects of small-scale spatial inhomogeneity in remote sensing data analyses and in the treatment of radiation in climate models, though studies and observations of the spectral dependence of cloud-radiation interactions are also limited. Significant progress in understanding the role of clouds in climate, especially regarding cloud-radiation budget relationships, is expected in the next several years because of an unprecedented suite of global and regional observation and analysis programs.

1. Introduction

This paper is part of a series of papers on satellite observations and climate.

Satellite observations of clouds have been utilized in atmospheric research ever since the first satellite images were returned (e.g., Arking 1964; Young 1967); but systematic progress in obtaining a quantitative understanding of global cloudiness has been slow. There are many ways to observe cloud properties and behavior; however, only satellites provide the overview of cloud systems at the scale of the synoptic weather systems in which they form. Moreover, satellites can directly observe the effects of clouds [the fundamental forcing of the atmosphere system (Hartmann et al. 1986)] on earth's radiation balance at the top of the atmosphere. A key obstacle to a determination of the climate's sensitivity to perturbations is understanding the nature of cloud-radiation feedbacks; hence, a global survey of cloud properties is a key objective of climate research programs (WCRP 1984). The datasets being collected by ISCCP, FIRE, NWPCRE, ICE, and ERBE[1] provide an unprecedented opportunity to improve our understanding of the role of clouds in climate. This brief review highlights the key research problems that can be attacked with these new datasets.

2. Data analysis

The basic steps in the analysis of satellite observations of clouds are three: detection, radiative modeling, and statistical characterization (cf., Rossow et al. 1985). The first step is the process of isolating those measurements that have some or particular types of clouds in them. In developing a cloud detection method, one must define the observable quantity that discriminates between cloudy and clear scenes, determine the amount of contrast present in this quantity (its range), and select the value of this quantity that divides cloudy from clear conditions. For example, one can detect cloud by an increase in the amount of solar reflectance at a particular location, either in contrast to a neighboring location or a neighboring time, but the success of this detection depends on 1) the amount of increase caused by clouds, as compared to other causes of increase that may be mistaken for clouds; 2) whether the reference value actually represents clear conditions at the target location and time; and 3) on the minimum amount of change that can be measured by the instrument. As another example, cloudy conditions may be indicated by an increase of the spatial variance of the visible radiances (Gutman et al. 1987); however, in some circumstances over deserts, cirrus or dust clouds do not produce any significant change in the spatial variance of the clear visible radiances (Sèze and Rossow 1988a). In other words, a particular measured quantity may not detect all occurrences of cloud under all circumstances at all locations on earth. Recent studies have begun to examine the systematic variations of cloud properties to define better cloud–clear discriminators

[1] The International Satellite Cloud Climatology Project (ISCCP) is the first project of the World Climate Research Program (Schiffer and Rossow 1983) and is associated with a number of field projects: the First ISCCP Regional Experiment (FIRE), a United States national project with participation by the United Kingdom and France (Cox et al. 1987); the Northwest Pacific Cloud Radiation Experiment (NWPCRE), a Japanese national project with participation by China; and the International Cirrus Experiment (ICE), a European project with participation by Germany, France, United Kingdom, and Switzerland. The Earth Radiation Budget Experiment (ERBE) is a NASA project with international participation (Barkstrom and Smith 1986).

Corresponding author address: Dr. William B. Rossow, NASA/GSFC, Institute for Space Studies, 2880 Broadway, New York, NY 10025.

(Minnis and Harrison 1984b; Coakely and Baldwin 1984; Desbois and Sèze 1984; Rossow et al. 1985; Saunders 1986; Sèze and Desbois 1987; Minnis et al. 1987; Sèze and Rossow 1988a,b; Rossow et al. 1988).

The second analysis step involves removal of other effects from the measurements in order to isolate the cloud contribution and the inference of specific cloud physical properties from the measured spectral radiances. The success of this step depends on the fidelity of the radiative transfer model used to analyze the data; however, it can also depend on the accuracy of specifying the other properties of the atmosphere and surface that also affect the satellite radiances. The usual situation encountered is that only a few of the relevant parameters needed for a complete analysis are available or measurable in a particular dataset; hence, a major objective is to define the best "effective" parameters that represent the primary effects of clouds on the measured radiation. Diagnosis of the relation of these radiative parameters to other physical cloud properties is necessary to extend observations to study of other cloud processes, especially precipitation. The radiative parameters begin to approach the physical properties of clouds as more information is included by the analysis of multi-instrument datasets collected from the same satellite. Although there are several such instrument combinations that have flown, e.g., an imager and a temperature–humidity sounder on the NOAA polar orbiters, no such multi-instrument analysis has been tried. The ISCCP analysis procedure (Rossow et al. 1985; Schiffer and Rossow 1985) represents the closest approach to implementation of this strategy: the analysis results of the NOAA polar orbiter sounder system (called TOVS) are used to specify the atmospheric temperature and humidity profiles in the analysis of the NOAA AVHRR (and other satellite) imaging data. Further development of such comprehensive multi-instrument data analysis techniques will be required to attain the objectives of the Earth Observing System (NASA 1984).

The third analysis step concerns the definition and determination of statistical measures of cloud behavior that lead to better conceptual understanding of the patterns seen in the satellite data. The most important statistics are those that characterize the predominant time and space scales of cloud variations and consequent radiation flux variations (cf. Brooks et al. 1986; Sèze and Rossow 1988a,b). This step is, in fact, linked to the first two, since measures of the same statistical quantities could be used to signal the presence of clouds in the data with more reliability and to define the most crucial radiative parameters. For instance, the contrast between a cloudy and clear scene is dependent on the magnitude of the cloud property variations in time and space, compared to those of the clear atmosphere and surface and the resolution of the satellite radiometer; knowledge of these statistics would refine the tests for the presence of clouds. Another example is the treatment of inhomogeneity in the modeling of cloud effects on radiation (Stephens 1988); the issue is whether the larger-scale radiation field can be modeled with large-scale cloud parameters without knowing about the smaller-scale cloud variations. This cannot be tested without first having some systematic way of describing the smaller scale variations.

Figures 1 and 2 illustrate the effect of different space and time resolutions on observed cloud variations. The impression Fig. 1 conveys is that at the largest and smallest spatial scales there are "large" regions of relatively uniform optical properties (usually thought of as cloudy and clear conditions), though some smaller-scale variations are still apparent at the highest resolution. At intermediate spatial scales there is a mixture of "larger" scale areas composed of a statistically uniform set of "smaller" elements, producing the characteristic "texture" of different cloud types (cf. Garand and Weinman 1986). Figure 2 suggests that the smaller spatial scale features and their precise locations vary rapidly in time, producing a reduction in contrast between "cloudy" and "clear" conditions and generally "smoothing out" the small spatial-scale structure of the clouds. This smoothing is even more noticeable when images are averaged over the diurnal cycle (not shown); contrast is reduced much more than averaging over several days at the same diurnal phase as in Fig. 2. Nevertheless, the positions and characteristics of the *larger*-scale features are remarkably constant in time when viewed at global scale.

Although the emphasis in this paper is on the improvement of satellite data analysis methods, the same knowledge of clouds that underlies better analysis methods is required to improve the modeling of clouds in weather and climate models. Thus, the research strategy is to search for understanding of the physical processes at work by using, testing, and improving remote sensing data analysis models that explicitly represent these physical processes, rather than being content with the direct use of the patterns in the data. Although such empirical approaches do provide insight into the patterns of cloud behavior that are present, their use in data analyses limits the results to the patterns *assumed* to be present, patterns which may not carry over to other problems. These patterns also may not be compatible with assumptions in climate models and, therefore, may not be "transferable" to models. An explicit model predicts these patterns from process calculations; discrepancies with the patterns in the data lead to improvements in the model and in our understanding of the processes. The same processes can be included in climate model parameterizations.

3. Cloud detection methods

The first cloud detection methods, the so-called (radiance) threshold methods, employ a simple test for the presence of cloud; namely, cloud is declared present

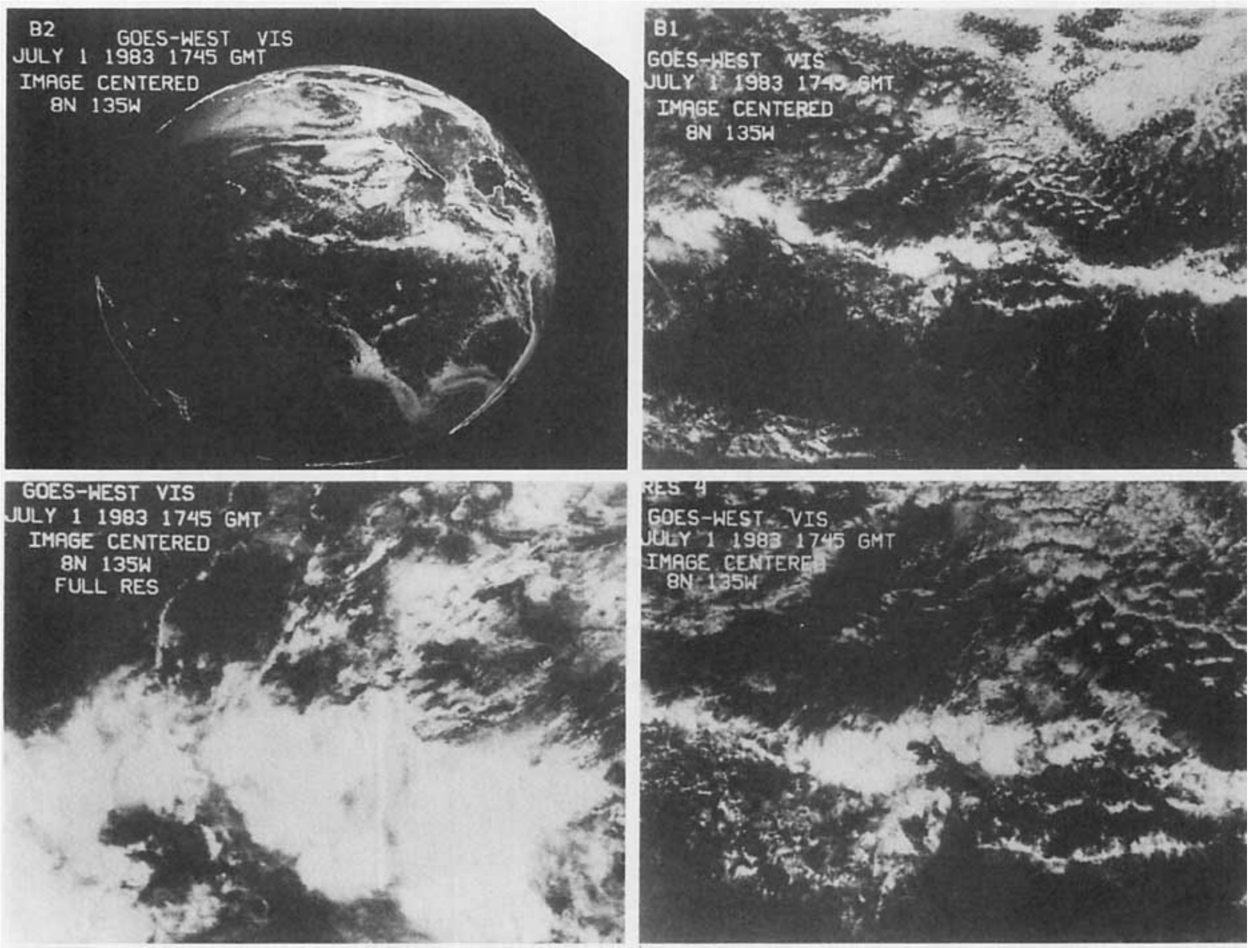

FIG. 1. A single visible image from GOES-4 (West) on 1 July 1983 displayed at four spatial resolutions: 32 km (upper left), 8 km (upper right), 4 km (lower right), and 1 km (lower left). Each image shows a progressively smaller portion of the same region centered at 8°N, 135°W.

if the satellite measured radiance is above or below some reference value which represents clear conditions. For example, Arking (1964) set a low value of the visible wavelength radiance by visual inspection of the satellite images; any larger value was declared to be a cloud. Since then, many single-test methods have been proposed (see Rossow 1981; Rossow et al. 1985; Rossow et al. 1988), but the essence of all these methods is that some parameter value must be above or below some reference one to indicate the presence of clouds. Actually, all decision processes are threshold methods in this sense, regardless of the quantities used for discrimination. The key research problem is to define the quantities and threshold values that provide the most sensitive and reliable separation of cloudy and clear conditions for the wide range of conditions encountered on earth (cf. Sèze and Rossow 1988a,b).

The proposed detection methods can be classified by whether they make use of radiance variations in wavelength, space, or time. Very few analyses have been based on spectral variations (see however, d'Entremont 1986; Inoue 1987; Raschke et al. 1987), although the determination of the vegetation index (Holben 1986) explicitly depends on the fact that cloud reflectance exhibits little spectral dependence from 0.5 to 1.0 μm, compared with the stronger dependence of vegetated surfaces, to eliminate clouds from satellite measurements. Even here, contrast is an issue since very sparse coverage by the vegetation (soils have weak spectral dependence) or snow cover can reduce the spectral contrast of the surface to values similar to that for clouds. Failure to detect persistent thin cirrus in the subtropics, e.g., can cause spurious seasonal variations in surface reflectances (cf. Matthews and Rossow 1987). Current limitations on the number and wavelengths of satellite radiometer channels, together with the complex variation of atmospheric and surface effects with wavelength, have inhibited the development of cloud analysis methods that rely on spectral signatures to detect clouds. Some studies have, however, used spectral signatures to identify specific cloud types (Shenk et al. 1976; Bunting and d'Entremont 1982;

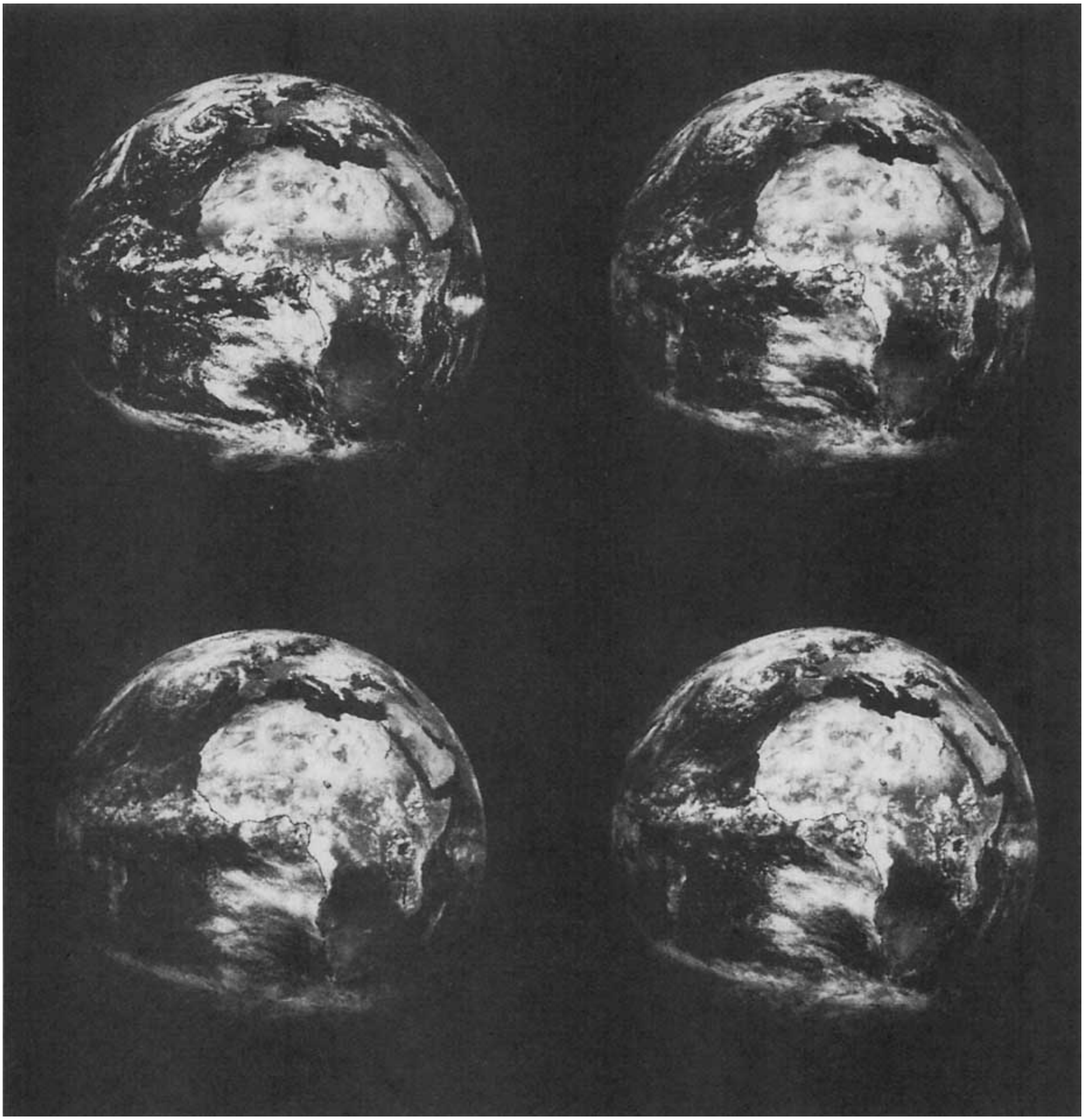

FIG. 2. Visible images from METEOSAT-2 at four time resolutions: (upper left) 30 min (single image from 12 July 1983), (upper right) 1 day (average of two images at the same time of day, 1 day apart), (lower right) 2 days, and (lower left) 4 days. The spatial resolution is 30 km near image center; all images are taken at local noon.

Platt 1983; Desbois and Sèze 1984; Arking and Childs 1985; Raschke et al. 1987; Inoue 1987).

The most common cloud detection methods rely on the spatial variation of the measured radiance(s) to detect clouds. This type of technique generally works well over a homogeneous surface that is represented by a radiance extreme, such as the ocean, since clouds usually exhibit significant small-scale spatial variability, especially at wavelengths near the visible part of the spectrum. This approach is also convenient because it relies only on information present in the particular satellite image being analyzed. Examples of this type of method are visible or infrared threshold methods (Arking 1964; Koffler et al. 1973) and bispectral methods (Shenk and Salomonson 1972; Arking and Childs 1985) that determine the reference radiance, usually an extremum, from an examination of the regional variation of radiances. Coakley and Bretherton (1982) define a different discriminator, namely, the magnitude of the small scale spatial variance in the infrared (although they must also test the magnitude of the radiance for completely overcast conditions, cf., Coakley and Baldwin, 1984). Several other statistical discriminators have also been studied (Desbois and Sèze 1984; Sèze and Rossow 1988a,b).

Over oceans the contrast between cloudy and clear conditions at visible wavelengths is generally high, making this type of detection very sensitive, but some broken boundary-layer cloudiness is almost indistinguishable from clear conditions in infrared over oceans. The success of a spatial variation test depends on the relation between the spatial scale of the cloud systems, data resolution, and the size of the region searched for clear conditions. If the region searched is too small, clear conditions may not be found; if the data resolution is too low, the characteristic small-scale variability of clouds may be missed, especially in low contrast situations. Coakley and Baldwin (1984), Saunders (1986), and Minnis et al. (1987) all propose additional tests to overcome these difficulties. Over an inhomogeneous surface, e.g., a desert, the spatial variability of clear scenes can become large enough to be confused with that of cloudy scenes (Sèze and Rossow 1988a,b); over snow and ice in the polar regions, cloudy and clear conditions are nearly indistinguishable at visible wavelengths (Raschke et al. 1987; Rossow et al. 1988). Consequently, methods that depend on spatial contrast, alone, are less sensitive over some land areas and the polar regions. Since the amount of variance or spatial contrast exhibited by clouds is also dependent on the resolution and sensitivity of the satellite radiometer (cf. Sèze and Rossow, 1988b), the success of this type of analysis can also be limited by data quality.

Another approach is to determine the presence of clouds from the time variation of the measured radiances; however, this is much more difficult in practice because it requires analysis of many satellite images that are properly aligned to represent the same locations and the removal of other effects that introduce time variations of the radiances. Examples of this approach are methods that use the time variations to identify a clear radiance, usually the extremum (Reynolds and Vonder Haar 1977; Minnis and Harrison 1984a; Rossow et al. 1988). Gutman et al. (1987) determine clear conditions in daytime by finding, among other tests, the minimum spatial variance of visible radiances for each location. Other discriminators have also been studied (Desbois and Sèze 1984; Sèze and Desbois 1987; Sèze and Rossow 1988a,b). As with the spatial variance methods, there is a contrast problem where some clouds exhibit very small time variations (e.g., tropical marine boundary layer clouds) or some clear areas that exhibit large variations (surface temperatures on midlatitude continents) producing confusing situations that are not properly analyzed (Rossow et al. 1985; Sèze and Rossow 1988a,b; Rossow et al. 1988). The time period searched in the analysis also matters. Some locations are characterized by significant diurnal variations of clouds but not the surface (e.g., marine boundary layer cloudiness, Minnis and Harrison, 1984b), whereas some land areas in the subtropics exhibit the reverse behavior (Duvel and Kandel 1985). In middle latitudes diurnal cloud variations are small, and diurnal land temperature variations are large (Minnis and Harrison 1984b); but synoptic time-scale cloud variations are large compared to surface temperature variations at constant diurnal phase (Sèze and Rossow 1988a).

Another type of method that has been studied is one which uses another independent data set to specify the clear radiance values (e.g., Stowe 1984; Stowe et al. 1988); for a global analysis the other observing system must provide information with the requisite space and time resolution.

Figure 3 illustrates this discussion by showing the distribution of radiances measured by a satellite over a geographic region at one time: the left-hand panel shows a case where the clouds form a distinct second population in the measured radiance, whereas the right-hand panel shows a case where there is no separation between the cloudy and clear populations. (This situation is encountered even at very high resolutions, cf. Welch et al. 1988.) Sèze and Rossow (1988a) illustrate comparable problems with time variations of cloud properties for some regions. Cloud detection methods that use specified clear radiances or radiance variations to determine clear conditions will all have difficulty obtaining a *definitive* separation of the cloudy and clear conditions in these "low contrast" cases. In this sense all cloud detection algorithms require a "threshold" because they must "decide" what (arbitrary) value of the selected quantity (radiance or its variation) divides the population into cloudy and clear parts.

A systematic test of some of these methods was conducted in the development of the ISCCP cloud analysis method (Rossow et al. 1985). Some of the difficulties suggested in the above discussion can be avoided if analysis is restricted to a particular climate regime; however, for global studies, a multiple test method seems necessary, such as those studied by Coakley and Baldwin (1984), Rossow et al. (1985), Saunders (1986), Minnis et al. (1987), Gutman et al. (1987), and Rossow et al. (1988). The major limitation on designing such a method is that some process must also be found to decide which of the many tests is working. Sufficient knowledge of the "types" of situations (a cloud climatology) must also be available to design a *complete* set of tests that covers all cases. Thus, the process of developing better analysis methods is interactive, involving analysis, validation, revision, and analysis again (cf. Coakley and Baldwin 1984; Rossow et al. 1988). The beginning of systematic surveys of the statistics of cloud properties, using these new methods, will lead to refined cloud detection methods (cf. Minnis and

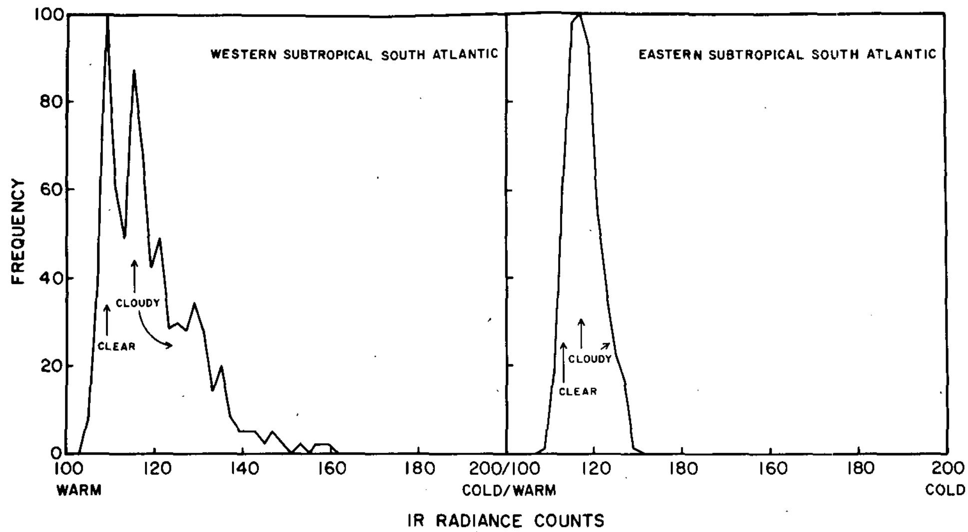

FIG. 3. Frequency histograms of IR radiance counts in an image at 12 UTC from METEOSAT-2 on 12 July 1983. Count 110 is approximately equivalent to a brightness temperature of 292 K. The observations are collected over two regions about 600 × 600 km in the western and eastern portions of the South Atlantic between 20° and 30°S latitude.

Harrison 1984a; Coakley and Baldwin 1984; Rossow et al. 1985; Minnis et al. 1987; Welch et al. 1988; Stowe et al. 1988; Sèze and Rossow 1988a,b; Rossow et al. 1988).

4. Cloud radiative models

The second analysis step involves removal of other effects from the measurements to isolate the cloud contribution and the inference of specific cloud physical properties from the measured spectral radiances. Our ability to model the (clear) atmospheric effects is quite good; the major limitation here is the accuracy of data specifying the properties of the atmosphere (e.g., Luther 1984); in particular, temperature and humidity information is often limited to *clear* conditions, which may bias calculations for cloudy situations. Modeling of surface effects is not yet as accurate as of the atmosphere (cf. Wetzel et al. 1984; Koepke and Kriebel 1987); however, the straightforward study of the same data used for clouds can lead to some significant improvements. In particular, analysis of existing satellite datasets [e.g., from ISCCP (Schiffer and Rossow 1985)] can lead to improved bidirectional models for various surface types (e.g., Briegleb et al. 1986; Koepke and Kriebel 1987). Currently, errors in modeling the surface effects are not a serious obstacle to cloud studies, except for thin or broken clouds. The major issue is whether or not we can model cloud effects on spectral radiances with sufficient fidelity.

The fundamental problem of modeling the wavelength and viewing geometry dependence of the interaction of clouds and radiation is the treatment of their vertical and horizontal inhomogeneity. Practical limits prevent a direct treatment of inhomogeneity on some scales. In the analysis of remote sensing data, the limit is the resolution of the satellite radiometer or the computer resources needed for the analysis, if the spatial and temporal resolution are too high. For ISCCP, such considerations led to sampling of the data at 3 h intervals and 30 km spacing; however, the dataset preserves the original image pixel size of about 5–10 km (Schiffer and Rossow 1985). For ERBE, the spatial resolution is about 30 km, but the time sampling is sparser (Brooks et al. 1986). In climate models, computer resources currently limit spatial and temporal resolution to 100–1000 km and 1–5 h. Thus, the problem of cloud inhomogeneity is primarily concerned with the effects of cloud variations on scales smaller than 10–100 km and 1–3 h, since the larger scale variations can, in principle, be represented explicitly.

Theoretical methods for treating vertical inhomogeneity are quite good, though not always practical. The doubling–adding technique (Hansen and Travis 1974) can calculate the vertical variations of radiative fluxes by dividing the atmosphere into many layers that are homogeneous over small extents. When combined with an efficient method for calculating spectral dependence, such as the correlated k-distribution method, the vertical variations can be calculated in a climate model (Hansen et al. 1983) with good success (Stephens 1984). However, observations of cloud vertical structure are very limited. Specific diagnostic studies provide key information about this aspect of clouds in storm systems (e.g., Houze and Betts 1981; Houze and Hobbs 1982; Herman and Curry 1984; see references in Rutledge and Hobbs 1984), but a global climatology is lacking. An extensive climatology of the correlated occurrence of cloud types, usually defined by altitude, is available from daytime surface weather observations (Warren et al. 1985); however, the vertical distribution of cloud optical or physical properties is not quantified.

Horizontal variations of cloudiness are usually formulated as variations of cloud cover fraction; i.e., variations of the optical properties of the atmosphere are represented by the presence/absence of two distinct conditions, "clear" and "cloudy," each with *different fixed* optical properties. Most general circulation models represent subgrid-scale cloud variations in this way (Stephens 1984), whereas the model of Hansen et al. (1983) uses the frequency of occurrence of total cloud cover in each model grid cell to represent partial cloudiness. Some satellite data analysis methods use this concept to estimate partial cloudiness in a single image pixel by assuming that radiance variations are produced predominantly by cloud coverage variations rather than by optical property variations (e.g., Reynolds and Vonder Haar 1977; Coakley and Bretherton 1982; Arking and Childs 1985). The continuity of the observed radiance distributions (Fig. 3), even at very high resolution (Welch et al. 1988), suggests, however, that "cloud cover" may represent an artificial division of a continuously variable optical medium into a two-point representation as "clear" and "cloudy" parts. The intuitive appeal of this division has led to an (almost) exclusive focus on determination of cloud cover fraction from data (cf. GARP 1975; Rossow 1981) and of the effects of cloud cover variation on climate (e.g., Cess 1976; Hartmann and Short 1980; Hartmann et al. 1986). However, variation of other cloud optical properties, together with cloud fraction variations, creates the potential for much more complex cloud-climate *feedbacks* (Wang et al. 1981), rather than a single cloud feedback.

Consideration of the scales of variation of the atmosphere's optical properties and the need to model the effects of these variations may still motivate a practical need for a "cloud amount" *parameter*, along with other optical parameters, in data analyses and climate models. In other words, it may be convenient to represent smaller-scale variations of the optical properties in a model as cloud amount variations. Stephens (1988) casts this problem in a form similar to that used to study turbulent motions and writes (schematically) the equation of radiative transfer for the radiance averaged over some scale as

$$\mu \frac{\partial \bar{N}}{\partial z} = -\bar{\boldsymbol{a}}\bar{N} + \int \bar{\mathbf{S}}\bar{N}d\Omega - \overline{\boldsymbol{a}'N'} + \int \overline{\mathbf{S}'N'}d\Omega \quad (1)$$

where $\boldsymbol{a}$ is a matrix operator containing the effects that are proportional to the radiance, such as bulk absorption and, in Stephens' study, the horizontal gradient of the radiance; and $\mathbf{S}$ is a matrix operator representing conservative scattering. In (1) the radiance is the sum of an average value and a fluctuating part, $N = \bar{N} + N'$, and, likewise, the optical properties of the medium are represented by the matrix operators $\boldsymbol{a} = \bar{\boldsymbol{a}} + \boldsymbol{a}'$ and $\mathbf{S} = \bar{\mathbf{S}} + \mathbf{S}'$. The fluctuation quantities represent variations on smaller scales than the averaging scale. Cloud amount is commonly used to denote the fraction of the area, H, with optical properties that are distinct from those of the remainder of the area (cf. Fig. 1 in Stephens 1988). This transforms Eq. 1 (following Stephens 1988) into

$$\begin{aligned}\mu \frac{\partial}{\partial z}[H\bar{N}_1 + (1-H)\bar{N}_2] &= -H\bar{\boldsymbol{a}}_1\bar{N}_1 \\ &+ H\int \bar{\mathbf{S}}_1\bar{N}_1 d\Omega - H\overline{\boldsymbol{a}'_1N'_1} + H\int \overline{\mathbf{S}'_1N'_1}d\Omega \\ &- (1-H)\bar{\boldsymbol{a}}_2\bar{N}_2 + (1-H)\int \bar{\mathbf{S}}_2\bar{N}_2 d\Omega \\ &- (1-H)\overline{\boldsymbol{a}'_2N'_2} + (1-H)\int \overline{\mathbf{S}'_2N'_2}d\Omega \quad (2)\end{aligned}$$

if $\bar{N} = H\bar{N}_1 + (1-H)\bar{N}_2$, $\bar{\boldsymbol{a}} = H\bar{\boldsymbol{a}}_1 + (1-H)\bar{\boldsymbol{a}}_2$, $\bar{\mathbf{S}} = H\bar{\mathbf{S}}_1 + (1-H)\bar{\mathbf{S}}_2$. Note that the "cloud amount" used to define the mean radiance and optical properties is the same, as usually assumed. Stephens (1988) also notes that the correlations of smaller scale radiance and cloud property variations within the "cloudy" (subscript 1) and "clear" (subscript 2) portions are usually neglected (e.g., Harshvardhan and Randall 1985; Stephens 1985).

Now consider the situation depicted in Fig. 4, where the radiance field over the domain is divided into two parts, H_N and $1 - H_N$ by a radiance threshold $\bar{N}_2 + \delta$ (much as is done with satellite data), but that the "true cloud amount" is defined to be H_p by a threshold in the optical properties (e.g., $\bar{\boldsymbol{a}}_2$, $\bar{\mathbf{S}}_2 + \Delta$). Assume that the measured "radiative cloud amount" overestimates the "true cloud amount," $H_N = H_p + \Delta H$, which is the usual assumption (cf. Coakley and Bretherton 1982; Arking and Childs 1985). Then, extending the result of Stephens (1988), Eq. (2) is modified to become

$$\begin{aligned}\mu \frac{\partial}{\partial z}[H_N\bar{N}_1 + (1-H_N)\bar{N}_2] &= -H_N\bar{\boldsymbol{a}}_1\bar{N}_1 \\ &+ H_N\int \bar{\mathbf{S}}_1\bar{N}_1 d\Omega - H_N\overline{\boldsymbol{a}'_1N'_1} + H_N\int \overline{\mathbf{S}'_1N'_1}d\Omega \\ &+ (\Delta H)\left[-(\bar{\boldsymbol{a}}_2 - \bar{\boldsymbol{a}}_1)\bar{N}_1 + \int (\bar{\mathbf{S}}_2 - \bar{\mathbf{S}}_1)\bar{N}_1 d\Omega\right] \\ &- (\Delta H)\left[-\overline{\boldsymbol{a}'_1N'_1} + \int \overline{\mathbf{S}'_1N'_1}d\Omega\right] + \Delta H\left[-\overline{\boldsymbol{a}'_2N'_1}\right. \\ &\left. + \int \overline{\mathbf{S}'_2N'_1}d\Omega\right] - (1-H_N)\bar{\boldsymbol{a}}_2\bar{N}_2 \\ &+ (1-H_N)\int \bar{\mathbf{S}}_2\bar{N}_2 d\Omega - (1-H_N)\overline{\boldsymbol{a}'_2N'_2} \\ &+ (1-H_N)\int \overline{\mathbf{S}'_2N'_2}d\Omega. \quad (3)\end{aligned}$$

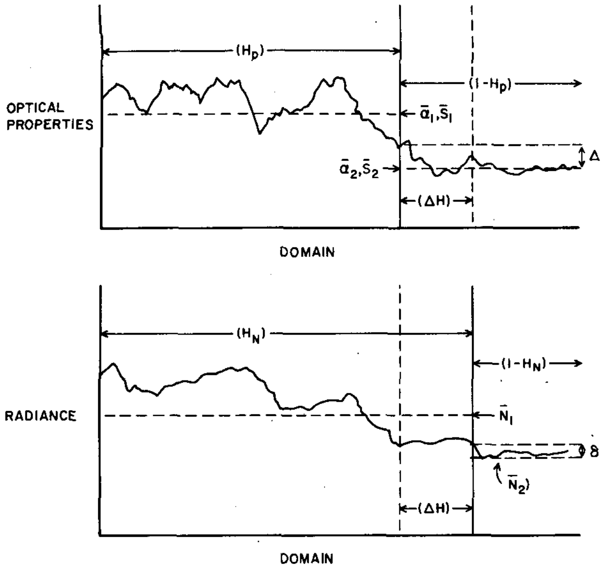

FIG. 4. (upper panel) Schematic of spatial variations of atmospheric optical properties and (lower panel) satellite-measured radiances. The upper panel divides the domain into a "cloudy" fraction, H_p, characterized by mean optical parameters, $\bar{\mathbf{a}}_1$, $\bar{\mathbf{S}}_1$ (see text Eq. 3), that exceed the mean "clear" optical parameters, $\bar{\mathbf{a}}_2$, $\bar{\mathbf{S}}_2$, by more than some threshold, Δ. The lower panel divides the domain by identifying the "cloudy" fraction, H_N, with a mean radiance, $\bar{N}_1$, that exceeds a mean "clear" radiance, $\bar{N}_2$ by a threshold, δ. The satellite "cloudy" fraction is assumed to exceed that defined by the optical properties by an amount ΔH.

Unlike the case considered by Stephens (1988), the dividing line between "cloudy" and "clear" conditions is depicted in Fig. 4 as more ambiguous, as suggested by Figs. 1, 2 and 3. Equation 3 illustrates the two effects of *defining* the cloud amounts in terms of two different criteria, namely a radiative threshold and a physical cloud property threshold. (Since both definitions are arbitrary, however, they need not be different.) In addition to the effects of the subscale variations, discussed by Stephens (1988), the bias effect (fifth term) and the edge effects (sixth and seventh terms) change the mean optical properties inferred from a measurement of $\bar{N}_1$ using an equation like (1) without the variation terms. The bias effect arises from averaging quantities attributed to "cloud" over some area that is "clear"; the (nonlinear) edge effect arises because a significant contribution to N'_1 may occur because of a "clearing." Both of these effects scale with the magnitude of the "cloud amount" overestimate, ΔH.

Use of satellite data to measure $\bar{N}_1$ and H_N and to infer $\bar{\mathbf{a}}_1$ and $\bar{\mathbf{S}}_1$ from these quantities produces *effective* cloud properties that actually *include* the effects of the smaller scale variations and imposes a specific definition of cloud amount. (The "proper" threshold in cloud optical properties could be defined by the magnitude of change required to produce a change in the mean radiance of a certain amount.) These effective values may constitute one form of "closure," valid for radiative problems (Stephens 1988). This approach partitions the total variation of optical thickness, say, into a variation of cloud amount and an effective optical thickness. What remains to be determined is whether the accuracy of the representation varies from one situation to another.

The magnitude of the extra terms in Eq. (3) determines the relation between the radiative parameters and other cloud properties and depends on 1) the scale over which the average is taken, 2) the scale of the optical property variations, and 3) the scale over which the radiation most strongly interacts with the optical property variations, which, together with item 2, determines the scale of the radiance variations. 1) For satellite observations, the averaging scale is 1–10 km; for climate model calculations this scale is 100–500 km. 2) Analysis results like those of Sèze and Rossow (1988a,b) and Welch et al. (1988) suggest that the more significant cloud property variations occur over the range 1–500 km, probably associated with the dominant scales of the dynamic motions. The amplitudes of the smaller-scale variations appear to be smaller than those of the larger-scale variations (Sèze and Rossow 1988a,b), just as the kinetic energy in smaller-scale motions is generally less than for synoptic scales. 3) The strength of the coupling between the radiation field and the cloud mass is highly variable with wavelength. At thermal infrared wavelengths, where the cloud is strongly absorbing, the physical distance corresponding to optical depth one is small, ~100 m–1 km. Since horizontal temperature variations in the atmosphere are small at these scales, the "error" terms involving fluctuations in Eq. (3) will be small (Stephens 1988). The exception to this is cirrus cloud where the small-scale optical property variations control the partial transmission of a large flux from the surface. At visible wavelengths, where the cloud does not absorb very much, the effective path length of photons is quite large, probably ≥5 km; and thus, the effects of smaller-scale cloud fluctuations may be weak.

Since the scale dependences of the terms in Eq. (3) can vary with cloud type, much work remains to understand how the smaller scale fluctuations, including those usually associated with cloud amount variations, must be treated to represent cloud-radiation interactions. In addition to obtaining statistical characterizations of the variations, tests are needed to determine what extra parameters are needed, beyond cloud amount and a mean quantity, like optical thickness, to calculate the radiative fluxes accurately. The discussion above implies that the "error" terms in Eq. (3) may not be very large when averaging over scales of 1–10 km; hence, measures of cloud property variations from current satellites may capture the more significant part of the problem. In other words, the definition of cloud amount *by the radiative analysis procedure which measures it* may prove useful in calculating the radiative effects of clouds. The ISCCP and its associated field programs provide the data to test this proposition.

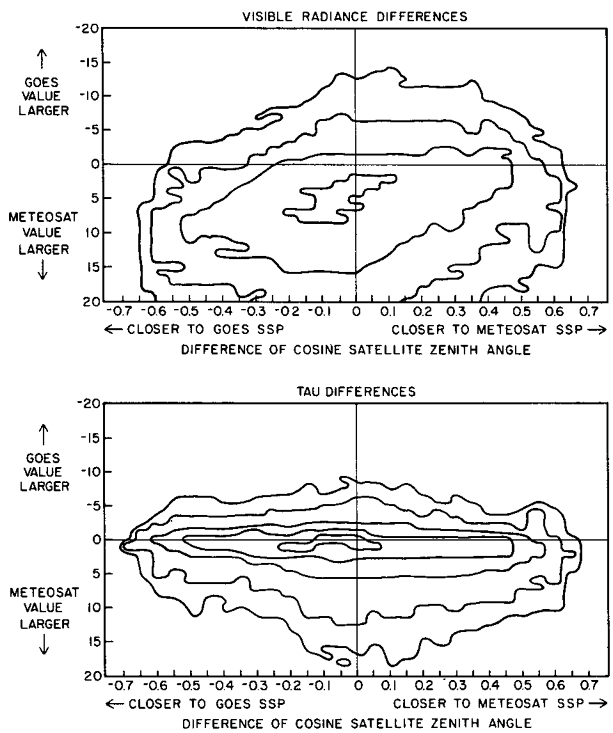

FIG. 5. Contours showing the two-dimensional frequency distributions of (upper panel) "cloudy" visible radiance differences and (lower panel) retrieved cloud optical thickness (TAU) differences as a function of the difference in the cosine of satellite zenith angle between GOES-5 (East) and METEOSAT-2 in July 1983. Both distributions peak in the center and the contours indicate successive factors-of-2 decrease in population moving out from the center. The sense of the sign of the radiance/TAU differences (vertical coordinate) and the cosine zenith angle differences (horizontal coordinate) is described in the figure. The upper panel shows that cloudy visible radiances generally appear brighter to the satellite viewing from larger zenith angles.

Validation of the radiative model requires intensive analysis of a complex dataset that includes quantities that are the input to the retrieval and quantities that can be predicted by the model using the retrieval results. Some results from such an analysis are shown in Figures 5 and 6. The narrowband visible and infrared radiances measured by two weather satellite imaging radiometers,[2] shown in the two upper panels, are expected to vary with viewing geometry, even if the properties of the underlying scene are constant (most of the data shown are over ocean). The visible radiances will vary with satellite zenith angle because of the path length dependence of ozone absorption and Rayleigh scattering, both small effects, and because of the strong anisotropy of cloud scattering (e.g., Hansen and Travis 1974; Stephens 1988). The infrared radiances will vary because of the path length dependence of water vapor (and cloud) absorption.

The ISCCP radiative model (Rossow et al. 1985; Schiffer and Rossow 1985) represents clouds as single, homogeneous layers with a specific water sphere size distribution, covering each satellite image pixel. The resulting interaction with the visible and infrared radiances is calculated including the full effects of multiple scattering and absorption. This model is applied to the radiances for pixels with scales from 4–16 km to retrieve optical thickness (at 0.6 μm) and cloud top temperature (corrected for transmission of IR radiances from below). Thus, pixel-to-pixel radiance variations are explained by optical properties that vary from pixel to pixel (i.e., on scales larger than about 10 km) and cloud amount is determined by the count of pixels with radiances above some background value. The retrieval of cloud optical parameters in each pixel attempts to describe their distribution explicitly so as to account for the angle dependence of the cloudy radiances.

The lower panels in Figs. 5 and 6 show one way to check the validity of this aspect of the model. Simul-

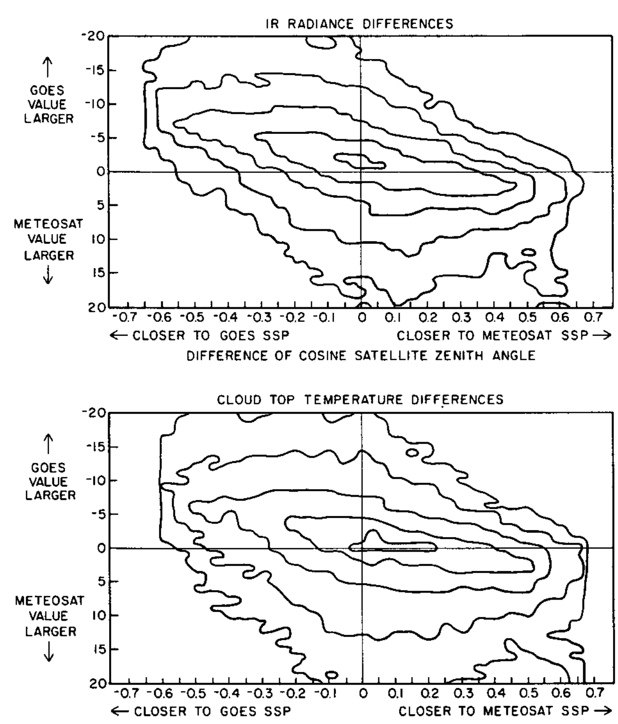

FIG. 6. Contours of the two-dimensional frequency distributions of (upper panel) "cloudy" infrared radiance differences and (lower panel) retrieved cloud top temperature differences as a function of the difference in the cosine of satellite zenith angle between GOES-5 (East) and METEOSAT-2 in July 1983 (see caption for Fig. 5 for details). The upper panel shows that cloudy infrared radiances generally appear colder to the satellite viewing from larger zenith angles.

[2] The data are from ISCCP where all narrowband radiances are normalized to the AVHRR reference standard (Schiffer and Rossow 1985). This normalization procedure uses colocated, simultaneous measurements of cloudy and clear scenes over the ocean from each geosynchronous satellite and the polar orbiter at the same viewing geometry. Even though the spectral responses of the visible channels for METEOSAT and GOES radiometers differ, the normalization removes the effects of the difference except for vegetated land surfaces. The slight bias between the METEOSAT and GOES data in Fig. 5 is caused by the inclusion of some land scenes.

taneous observations of colocated scenes[3] are collected from two satellites (in this case METEOSAT-2 and GOES-5). The upper panels compare the radiances directly as a function of the difference in the cosine of the satellite zenith angles. The lower panels compare the optical parameters retrieved for each satellite using the model. If the model's treatment of the angular dependence is correct, then the retrieved optical parameters should have the same value for both satellites for all angles; in effect, the retrieved quantity and model are used to predict radiances measured at other viewing geometries. (Note that the analyses of the two datasets are completely independent, including the clear sky radiance values obtained.) Figure 5 shows that the visible channel model seems to correctly account for the angle dependence, but in Fig. 6 the infrared channel model does not do so completely.

The behavior shown in Fig. 5 for the visible radiances is a surprise, since several studies have suggested that broken cloudiness or cloud fields composed of irregular, finite cloud shapes should exhibit significant departures from plane-parallel model behavior[4] (cf. Mckee et al. 1983; Harshvardhan and Thomas 1984; Davies 1984). A possible explanation is that, since the pixel size is of order or greater than the path length for visible wavelength photons, multiple scattering within and between clouds eliminates most deviations from layer-cloud behavior (cf. McKee et al. 1983). Thus, even though the model does not explicitly represent small-scale inhomogeneities, the retrieval of an area-averaged parameter appears to represent the area-averaged radiance angular distribution at this wavelength; i.e., the nonlinear contributions of the extra terms in Eq. (3) are small.

Since the observations compared in Fig. 5 are simultaneous and colocated, each pair of observations has the same solar zenith angle. The principle of reciprocity[5] (Chandrasekhar 1960) implies that the validity of the model for varying satellite zenith angles extends to varying solar zenith angles. The two satellites view these locations at different azimuths, but no differences in the retrieved optical thicknesses with varying solar zenith and azimuth angles were found. These results were also examined as a function of optical thickness, itself; no differences were found, but the statistics are very sparse and require further study. Larger datasets are required to examine this agreement for different cloud types, at higher spatial resolutions, at more extreme viewing geometries, and at other wavelengths.

In the infrared (Fig. 6), the deviation from agreement with the model behaves like an additional, but unexpected pathlength dependence. In the model the cloud is represented as a homogeneous layer, meaning that there is assumed to be no temperature variation over the vertical extent of the cloud; thus, the radiation is modeled as isotropic. The surface radiation transmitted by thinner clouds is not isotropic in the model, however. One possible explanation for the disagreement is that most cloud systems are diffuse enough in their upper levels that the vertical variation of temperature within the cloud introduces an additional pathlength dependence in the IR radiation. This is supported by the fact that the correction for transmitted radiation through thinner clouds reduces the discrepancy to the magnitude shown. However, the fact that the magnitude of the effect does not seem to depend on the inferred optical thickness of the clouds may be explained by a more general, but undetected presence of thin cirrus over thicker cloud systems. Another possible explanation for this behavior, particularly its increasing magnitude with increasing temperature contrast between cloudy and clear conditions (not shown), is that most clouds have "holes" (optically thinner or clear regions); the projected area of these holes varies with satellite zenith angle in a way that would cause the behavior shown in Fig. 6 (Ellingson 1982; Harshvardhan and Weinman 1982; Naber and Weinman 1984). More detailed studies of this preliminary result are needed.

The spectral dependence implied by the retrieval model could be checked by using the cloud parameters retrieved from the narrowband radiances by ISCCP in a model to predict the broadband radiances measured by ERBE (or vice versa). Other cloud attributes, that must be assumed in the analysis of satellite observations, can also be verified by more detailed observations of the cloud from other "platforms". The FIRE project is collecting measurements from satellites, aircraft, and ground instruments to validate more aspects of the radiative models by providing simultaneous, colocated observations that differ in spectral coverage and resolution, spatial and temporal coverage and resolution, and viewing geometry (Cox et al. 1987).

5. Statistical studies of clouds

The third step in the analysis procedure determines the most significant statistics of cloud variations that constitute our understanding of the phenomenon. Employing improved cloud representations in data analysis models or climate models first requires that the nature of cloud variations on different space and time scales be quantitatively ascertained. A preliminary result of such studies, using the analysis from ISCCP, is presented in Figs. 7 and 8 to illustrate the type of

[3] Since the actual observations are neither precisely simultaneous nor collocated, their comparison can only be statistical (cf. Sèze and Rossow 1988b). The dispersion of differences values in Figs. 5 and 6 is similar in magnitude to the differences produced by a different space/time sampling of data from a single satellite.

[4] Note that the radiation field calculated for a plane-parallel cloud model is not necessarily isotropic.

[5] This principle states that the equations of radiative transfer are invariant to a transposition of the angles of incident and departing radiation.

research that is needed (see, also, Sèze and Rossow 1988a,b).

Figures 7 and 8 return to the question of cloud cover fraction by illustrating the distribution of "cloud fraction" that occurs for different spatial and temporal aggregation scales. Here, cloud fraction is defined to be the fraction of total image pixels (size $\approx$ 10 km) in a region of size about 250 km that are determined to contain some cloud. At the smallest scales (250 km and 3 h), about half of the regions are either completely overcast or completely clear; the global average cloud cover in these particular results is about 60%. There are less cloud-free and more completely cloudy regions over ocean than land. As the aggregation scales are increased to 2000 km and 1 month, however, the distribution shifts to one where most regions are characterized by partial cloud cover (cf. Hughes and Henderson-Sellers 1983). This result can be understood in terms of the "general" occurrence of clouds in systems that are larger than 250 km, but smaller than 2000 km (cf., Fig. 1), and time scales for variation larger than 3 h, but smaller than 30 days (cf., Fig. 2). Variations on smaller space and time scales, which are also of importance for remote sensing data analysis models, suggest that some significant variations still occur at spatial scales $\approx$ 30–100 km (Sèze and Rossow 1988a,b), particularly in the tropics, which may need to be included in climate model treatments of radiation. Confirmation of this type of result has obvious importance to climate model representations of clouds.

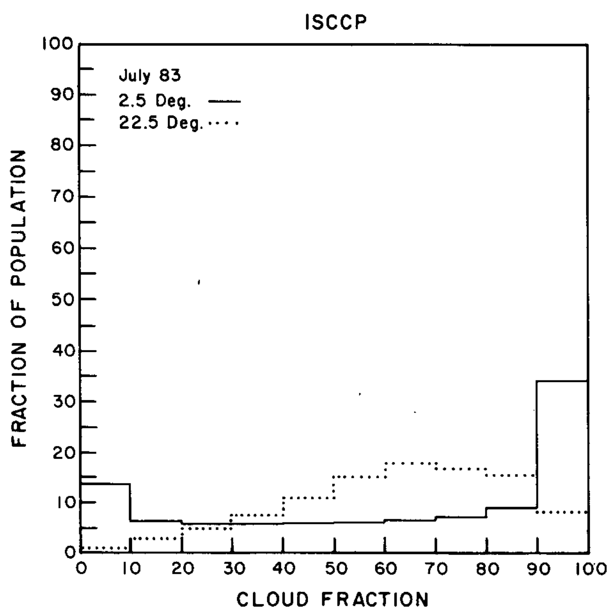

FIG. 7. Global distribution of regional cloud fractions, determined by counting the number of cloudy satellite image pixels in the region, for two region sizes: 2.5°-equivalent equal-area (solid line) and 22.5°-equivalent equal-area (dashed line). Time resolution is 3 h. Equal-area regions have indicated latitude increments and variable longitude increments to maintain approximately equal areas. Original pixels represent areas of about 4–16 km. The data analyzed are the ISCCP B3 data for the month of July 1983; the cloud detection method is the ISCCP cloud algorithm.

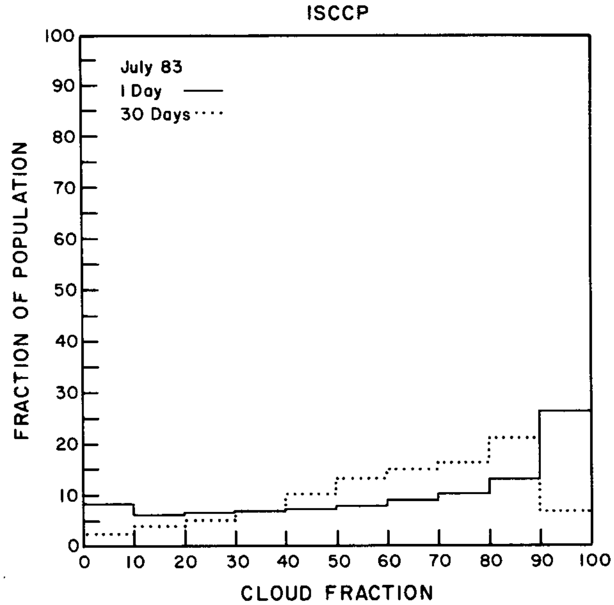

FIG. 8. Global distribution of regional cloud fractions, determined by counting the number of cloudy satellite image pixels in a 2.5° equal-area region, as a function of averaging time period: (solid line) 1 day and (dashed line) 30 days. See caption for Fig. 7 for details.

6. Assessment

The simultaneous collection of several global cloud climatologies,[6] two global radiation budget datasets,[7] and several detailed datasets representing coordinated intensive cloud studies[8] presents an unprecedented opportunity to tackle the issues raised in this review. The multispectral, multiscale, multidirectional observations contained in these datasets, when combined in a comprehensive analysis, allow for a thorough examination of the relations between observed radiances and cloud properties (remote sensing problem) and between cloud properties and radiation budgets (climate model problem).

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[6] ISCCP (narrowband radiances plus radiative model analysis) (Schiffer and Rossow 1983); NIMBUS-7 (narrowband radiances) (Stowe 1984; Stowe et al. 1988); and conventional ground-based weather observations (Warren et al. 1985).

[7] ERBE (Barkstrom and Smith 1986) and NIMBUS-7 ERB (Jacobowitz et al. 1984) (broadband radiances plus empirical angle dependence model).

[8] FIRE (Cox et al. 1987), NWPCRE, ICE, (surface, aircraft, and high resolution satellite radiances plus in situ samples and conventional weather observations).

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